

Heavy metal removal by means of electrocoagulation using aluminum electrodes for drinking water purification

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Abstract The present study has investigated the performance of electrocoagulation, to produce drinking water, using aluminum electrodes to remove nickel (Ni) and chromium (Cr) from two different water well samples from the north of Italy. Different experimental parameters, such as stirring and distance between the electrodes and current density, have been examined for both water samples. The series of experiments carried out on these two water samples has shown that the removal process of Ni is faster than that of Cr. In the case of water poisoned by Ni, a final concentration of 5 ppb was achieved starting from 41 ppb, while the Cr case showed a final concentration of 10 ppb compared to an initial 20 ppb. The electrocoagulation treatment presented in this study has shown very promising results and a high potential to remove very low amounts of heavy metals from water for drinking water production purposes.

Keywords Nickel · Chromium · Electrocoagulation · Drinking water · Aluminum

1 Introduction

The presence of nickel (Ni) and chromium (Cr) in drinking water is a ubiquitous problem. The assimilation of large amounts of Ni can cause several kinds of cancer of the lungs, nose, larynx, prostate, etc., as well as other diseases such as asthma and allergic skin reactions [1–3].

Chromium(VI) is toxic and is carcinogenic in non-lethal levels. Moreover, it can irritate the eyes, skin, and mucous membranes [4, 5].

Water for human consumption should not contain more than 20 ppb of Ni and 50 ppb of Cr according to the “World Health Organization Guidelines for Drinking-water Quality.” The Turin drinking water company Società Metropolitana Acque Torino (SMAT), which is responsible for providing high-quality standard water to the Turin municipality, has fixed even lower values, in terms of the amount of Cr and Ni: less than 10 ppb for Cr and 5 ppb for Ni. For this reason, a very efficient technology to achieve such low-removal targets is required.

The most commonly used methods for the removal of metals from water are: coagulation/filtration, ionic exchange, and reverse osmosis [6]. All these techniques require multi-step procedures and a post-treatment. Electrocoagulation (EC) is an effective low cost treatment which could be adopted as an interesting alternative process. This technique has been compared with chemical coagulation, and has shown high removal efficiency [7–9]. The EC process involves the in situ generation of a coagulant through the electro-oxidation of a sacrificial anode and it offers many advantages. The most important ones are:

- no requirement of additional chemicals;
- removal of different kinds of pollutants;
- no need for a pH control;
- only simple equipment is needed and it is easy to operate;
- the flocs generated by EC are similar to chemical flocs, although EC flocs tend to be much larger, contain less bound water, they are more acid-resistant and more stable and they can therefore be quickly separated by

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filtration, which results in low sludge production [10–12].

The gas bubbles produced during electrolysis can carry the contaminant to the top of the solution, where it can be more easily concentrated, collected, and removed [10–12].

The EC process is carried out in three successive stages:

- formation of coagulants through electrochemical oxidation of the “sacrificial electrode”;
- destabilization of the contaminants, particulate suspension, and breaking up of the emulsions;
- aggregation of the destabilized phases to form flocs [12–14].

In the EC process, the Faraday’s law describes the relationship between the current density and the amount of aluminum (Al) that goes into the solution, if the amount of evolved oxygen is negligible. Even though the amount of dissolved Al can be roughly estimated on the basis of Faraday’s law, it is very difficult to correlate this amount with the abatement of the contaminant. Moreover, it is known that in some cases the amount of chemically dissolved Al in the proximity of the cathode, due to the increase in pH, provides an important contribution to the totally dissolved Al [15]. A common approach to this problem is through empirical correlations taking into account both physico-chemical aspects of flocculation and the geometry of the electrode assembly, including the operating conditions of the cell.

When the energy balance of the cell is needed, e.g., for an estimation of the cost of the process, all the dissipation terms must be considered, to evaluate the relationship between the voltage applied to the cell and the current density. To this end, the different components of the cell voltage must be taken into account: the activation overpotential for both anodic and cathodic reactions, concentration overpotentials, and ohmic dissipation mainly due to the electrolyte resistance.

Concentration overpotential, also referred to as mass transfer or diffusion overpotential, arises from the concentration gradient which is established when a given current flows within an electrochemical cell, as a result of the consumption of reagents at the electrode surface and the consequent mass transfer (diffusional) mechanism to replace them. Concentration overpotential may also appear when an ionic species (e.g., Al^{3+}) is produced by the electrochemical reaction at the electrode surface, and diffuses to the bulk of the electrolyte. Kinetic or activation overpotential is caused by the activation energy barrier corresponding to the charge transfer step of the electrochemical reaction mechanism. The activation overpotential is particularly high for the evolution of gases on certain electrodes. All the dissipative terms, both overpotentials

and ohmic drop (IR) in the electrolyte, increase as the current increases; the IR-drop is also related to the geometry of the cell (distance and surface area of the electrodes) and the conductivity of the electrolyte solution. The IR-drop can be minimized by decreasing the distance between the electrodes, and increasing the cross-sectional area of the electrodes and conductivity of the solution [7, 11].

EC is a popular method for the abatement of hexavalent Cr from wastewater. When iron anodes are used, in addition to direct removal of Cr(VI) by electrocoagulation, the reduction to Cr(III) followed by precipitation as $\text{Cr}(\text{OH})_3$ must be considered [16–18]. In the case of wastewater treatment, a wide range of concentration has been considered for Cr, from 50 to 2,000 ppm, usually with the aim of obtaining a residual concentration of about 0.5 ppm [19–22].

In the case of Ni, good results were obtained by EC, with a removal efficiency of 98 % compared to an initial pollutant concentration of 60 ppm [13, 23].

The scope of the present study is to prove the feasibility of the EC process to abate Cr and Ni to the range of ppb in drinking water treatments. To the best of our knowledge, such a result has not been published in the literature, where the majority of works deal with wastewater treatments. The experimental approach to evaluate the efficiency of electrocoagulation using Al electrodes was planned to investigate a well water treatment to abate an initial concentration of Ni of about 40 ppb, and of Cr of about 20 ppb. Operating conditions, such as agitation, distance between the electrodes, current density as well as the applied voltage to minimize the power consumption, were considered.

Furthermore, after 50 h of electrolysis, the electrodes were examined by means of scanning electron microscope (SEM) analysis, to provide additional information on the degradation of the electrodes.

2 Experimental

Electrocoagulation with Al electrodes was investigated using two real water samples, provided by SMAT, from two municipalities in the province of Turin (sample A, Ni = 41 ppb and sample B, Cr = 23 ppb). These well water samples will hereafter be indicated as samples containing Ni and Cr, respectively. The conductivity, the pH, and the most important ion species of these samples are reported in Table 1.

Electrolysis was carried out using a batch glass reactor containing 400 ml of the water sample and two 1 mm-thick Al electrodes (purity 99.999 %) specific area 25 cm^2 ($5 \times 5 \text{ cm}$), as the anode and cathode.

Before each test, the electrode surface was mechanically polished with WS-FLEX 18-C sandpaper, scrubbed with 15 % HNO_3 , rinsed with distilled water, and then treated in

Table 1 Characteristics of the A and B water samples

Sample	Ca ²⁺ (ppm)	Mg ²⁺ (ppm)	Cl [−] (ppm)	pH	Conductivity ($\mu\text{S cm}^{-1}$)
Nickel (A)	10.675	12.65	4.25	7.41	191.3
Chromium (B)	102.4	20.75	9.5	7.33	505.6

an ultrasonic bath at 40 °C for 1 h to ensure surface reproducibility. The electrodes were connected to a DC power supplier for 120 min, and the current density was kept constant during the tests. The current density in each run was in the 0.2–1.6 range (mA cm^{-2}).

The first EC experiments were conducted for 120 min, with and without stirring, at 600 rpm using a Teflon-coated magnetic stirrer. The distance between the electrodes was 1 cm and the current density was 0.2 mA cm^{-2} . Subsequently, the distance between the electrodes was decreased to 0.5 cm, to reduce the cell voltage and energy consumption. Finally, tests were carried out at different current densities at 0.2; 0.4; 0.8; and 1.6 mA cm^{-2} at 600 rpm with the purpose of finding the best removal conditions. All the experiments were conducted at 25 °C.

The treated water was sampled at 0, 10, 20, 40, 60, and 120 min, filtered in pure cotton pulp with a pore size of 5–6 μm , and analyzed by means of ion chromatography (ICS 1100 Dionex) to determine the amount of Ni, Cr, and Al ions in the solution. Other parameters, such as pH and conductivity (ION450 Ion Analyzer, Radiometer Analytical), which are fundamental for investigation of the electrocoagulation process, were also measured.

After 50 h of electrolysis of both the investigated water samples, the electrodes were examined by means of SEM (FESEM/EDS Leo 50/50VP with a Gemini column) to provide additional information on the degradation of the electrodes.

3 Results and discussion

In this study, the electrocoagulation process has been evaluated as a technological treatment for drinking water production. The operational conditions of the EC process depend on various operating parameters, such as the type of pollutant, distance between the electrodes, current density, and agitation. The effects of these parameters have been investigated to enhance the process performance.

3.1 Effect of agitation and mass transfer phenomena

In order to evaluate the influence of the stirring on the EC treatment, experiments have been carried out with two different well-water samples, running the same test with or without stirring at 600 rpm for 120 min. Table 2 depicts

the results obtained when the current density was fixed at 0.2 mA cm^{-2} with 1 cm of gap between the electrodes, for both Ni and Cr water samples.

For both samples, a lower metal removal was observed for the tests without stirring. In the case of Ni, the amount of metal decreased from 41 to 22 ppb, while Cr decreased from 23 to 20 ppb. However, when the solution was stirred, the removal efficiency was higher, reaching a final metal concentration of 16 ppb for Ni and 19 ppb for Cr. It should be pointed out that the removal target set by SMAT was not reached in either case. However, in the experiments that were carried out, the abatement of Cr was lower compared to Ni. It can be observed in Table 2 that the Al concentration does not exceed the value recommended by WHO (200 ppb). Only under stirring conditions, a slightly larger amount of Al (208 ppb) was found after 120 min, due to the enhancement of Al^{3+} diffusion from the anode surface to the bulk solution [9, 11].

Considering the cell voltage, when the solution is stirred, the applied voltage is ever lower than the case without stirring (Table 2). The difference in the cell voltage in the experiments with and without stirring is due to the fact that turbulence helps the Al ions reach the bulk solution from the anode surfaces and reduces the concentration (mass transport) overpotential [14]. Moreover, a difference in the final conductivity was observed: water sample A, $161.8 \mu\text{S cm}^{-1}$ at 600 rpm compared to $153.68 \mu\text{S cm}^{-1}$ for the experiments without agitation. A similar behavior has been observed for the water sample B (440 and $431 \mu\text{S cm}^{-1}$, respectively).

The pH, remained between 7.2 and 7.8 in all the experiments, a range that facilitates the formation of $\text{Al}(\text{OH})^{2+}$, $\text{Al}(\text{OH})_2^+$, and $\text{Al}(\text{OH})_3^0$ [26].

The aforementioned results confirm that, with our experimental set-up, stirring definitively enhances the performance of the whole EC treatment. The anodic electrochemical reaction that produces Al^{3+} is faster compared to the diffusion of such species to the bulk solution. In fact, the flocculation process is known to be enhanced by soft mixing. Therefore, given the impact of stirring on species removal, all the subsequent experiments were carried out with an agitated solution.

3.2 Effect of distance between the electrodes

In order to enhance the process efficiency, in terms of energy consumption, the IR-drop can be minimized by decreasing the distance between the electrodes and/or increasing the solution conductivity [7, 11]. The examined samples are from well-water, in which the addition of chemical agents was not investigated, therefore the conductivity could not be modified. For this reason, some experiments were carried out by changing the gap between

Table 2 Pollutant removal, Al release, potential, pH, and conductivity in non-stirred and stirred (600 rpm) conditions

	Time (min)	0	10	20	40	60	120
Nickel							
Ni (ppb)	0 rpm	41	38	36	32	28	22
	600 rpm	41	34	33	26	22	16
Al (ppb)	0 rpm	0	111	65	89	123	69
	600 rpm	0	132	136	184	190	200
Potential (V)	0 rpm	3.10	3.30	3.70	4.15	4.37	5.01
	600 rpm	3.10	3.21	3.32	3.36	3.45	3.50
pH	0 rpm	7.41	7.51	7.59	7.61	7.72	7.78
	600 rpm	7.41	7.53	7.73	7.87	8.02	8.06
Cond. ($\mu\text{S cm}^{-1}$)	0 rpm	191.3	171.9	162.1	162.5	163.9	153.6
	600 rpm	191.3	172.6	162.8	163.2	161.3	161.8
Chromium							
Cr (ppb)	0 rpm	23	23	23	22	21	20
	600 rpm	23	23	22	21	20	19
Al (ppb)	0 rpm	0	8	55	75	71	62
	600 rpm	0	60	156	100	121	208
Potential (V)	0 rpm	2.60	3.02	3.22	3.72	3.84	4.34
	600 rpm	2.60	3.26	3.30	3.29	3.30	3.20
pH	0 rpm	7.33	7.40	7.57	7.66	7.70	7.78
	600 rpm	7.33	7.43	7.63	7.90	7.95	8.97
Cond. ($\mu\text{S cm}^{-1}$)	0 rpm	505.6	468	462	461.0	459.0	439.0
	600 rpm	505.6	482.0	477.0	457.0	447.0	444.0

the electrodes, for the two different well water samples (containing Ni and Cr, respectively), at a fixed current density of 0.2 mA cm^{-2} under 600 rpm stirring.

Figure 1 shows the cell voltage during the experiments when the distance between the electrodes is 1 and 0.5 cm. It can be observed that the voltage decreases in all the experiments when the gap between electrodes is 0.5 cm.

The change in the electrodes distance has an important influence on energy consumption. Even though the electrocoagulation experiments in the present study have been carried out in a simple batch glass cell, a rough estimation of the energy consumption was computed with reference to the volume of the treated water. For a current density of 1.6 mA cm^{-2} , a value of about 1.74 kWh m^{-3} was found when the gap between the electrodes was 1 cm, while a lower value of about 0.48 kWh m^{-3} was obtained in the case of 0.5-cm gap.

As far as the costs determined by consumption of the sacrificial anode are concerned, no change was observed when the gap between the electrodes was varying. Hence, all the cost reductions are obtained from the decrease in energy consumption, due to shorter distance between the electrodes. Therefore, all the subsequent experiments were performed considering a gap of 0.5 cm.

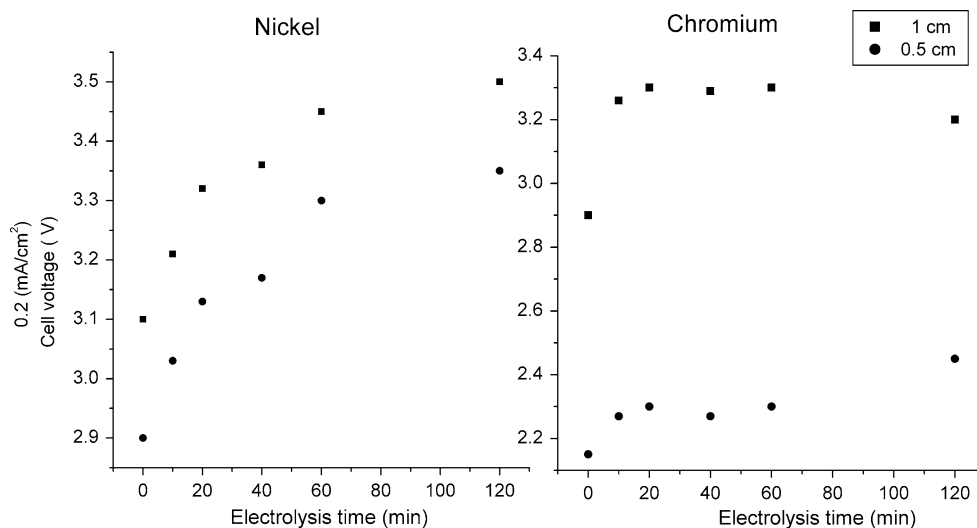
In addition to the beneficial effect on energy consumption, we also observed a slight improvement in the

contaminants abatement by reducing the gap between the electrodes. Since the scope of the present study was to obtain preliminary information on the feasibility of the EC process to abate Cr and Ni in the range of ppb, this point was not discussed; but a possible increase in performance can be related to the optimization of the ratio between the solution volume and the electrode surface.

3.3 Effect of the current density

The current density not only determines the amount of coagulant that is generated, but also the rate of formation and size of the gas bubbles evolving on the electrode surface, which help enhancing the mass transport of both Al^{3+} and OH^- to the bulk solution [9]. Figures 2 and 3 show the experiments carried out at a fixed current density of 0.2, 0.4, 0.8, and 1.6 mA cm^{-2} . All the experiments were performed with an inter-electrode gap of 0.5 cm and stirring the solution at 600 rpm. Based on our experimental set-up, the Al dosage after a 2-h treatment ranges from 0.3 mM l^{-1} (at 0.2 mA cm^{-2}) to 2.5 mM l^{-1} (at 1.6 mA cm^{-2}). Figures 2A and 3A show the Ni and Cr concentration during the experiments. As expected, it can be observed that by increasing the current density a higher removal rate is obtained, and the final concentration value of Cr and Ni is notably decreased. Though the quantitative results for Ni and

Fig. 1 Variation in the cell voltage during the electrocoagulation process with an inter-electrode gap of 1 and 0.5 cm, for the samples containing Ni and Cr respectively, for a fixed current density value of 0.2 mA cm^{-2} in stirred solutions at 600 rpm



Cr abatement are substantially different, the concentration profile is quite similar for both samples, showing an almost exponential decrease in the metal concentration during the electrocoagulation process. For the Ni-containing sample (Fig. 2), after 60 min of treatment, a metal removal in the range of 50–78 %, depending on the current density, was observed; then the removal rate decreased, providing a Ni removal of 60–93 % after 120 min.

Figure 3 shows the concentration profile for Cr abatement. It can be observed that the removal of Cr is slower than that of Ni. After 60 min an abatement of 17–25 % is reached, while the removal of Ni for a given condition (e.g., 0.2 mA cm^{-2}) is 3 times higher than that of Cr. The target fixed by SMAT was achieved after 60 min at 1.6 mA cm^{-2} and after 120 min at 0.8 mA cm^{-2} by varying the current density.

In order to present the abatement data in relation to the coagulant dosing, as a consequence of the anodically dissolved Al, Figs. 2B and 3B also show the Ni and Cr normalized (C/C_0) concentration profiles versus the amount of passed charge. It can be observed that, in spite of rather dispersed data due to our experimental set-up, some correlation is visible between the concentration decrease, for the various current densities, and the charge passed up to about 20 mAh l^{-1} . This is more evident for Ni, for which an abatement of about 65 % is obtained with a charge of $40\text{--}60 \text{ mAh l}^{-1}$. The abatement of Cr is less effective (25 % for a similar amount of charge) and much more dependent on the current density. It must be noted that in the Cr containing sample the initial metal concentration C_0 is lower, about one half of that in the case of Ni containing sample.

The removal of metals is affected to a great extent by the pH of the solution, which changes during the process. Figure 4 shows the trend of pH for the Ni (sample A) and

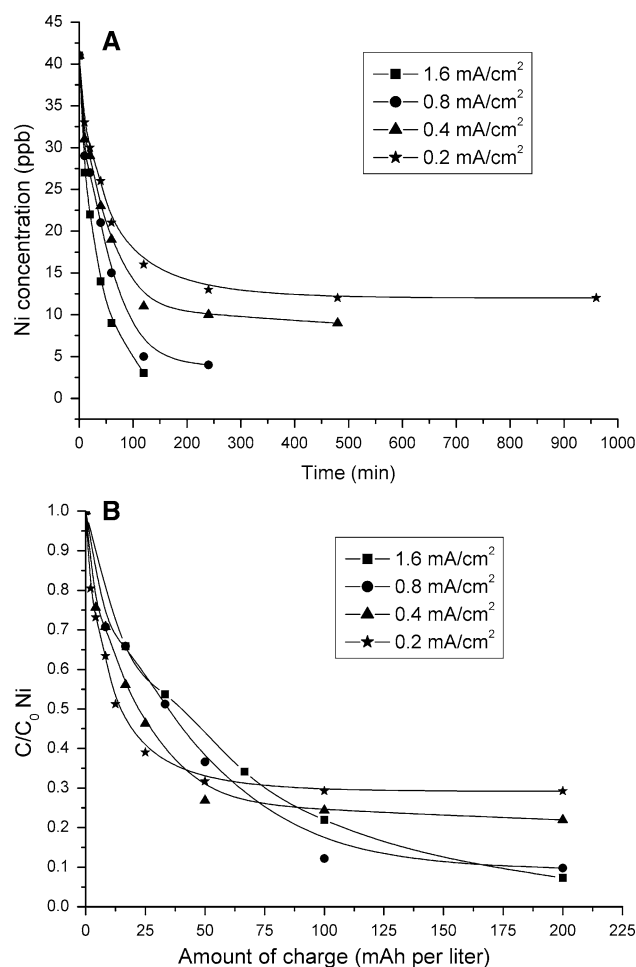


Fig. 2 Evolution of Ni concentration during electrocoagulation tests at different current densities: 0.2, 0.4, 0.8, and 1.6 mA cm^{-2} ; distance between the electrodes of 0.5 cm, stirred solution at 600 rpm. Concentration profile versus time (A), normalized concentration C/C_0 versus the amount of passed charge (B)

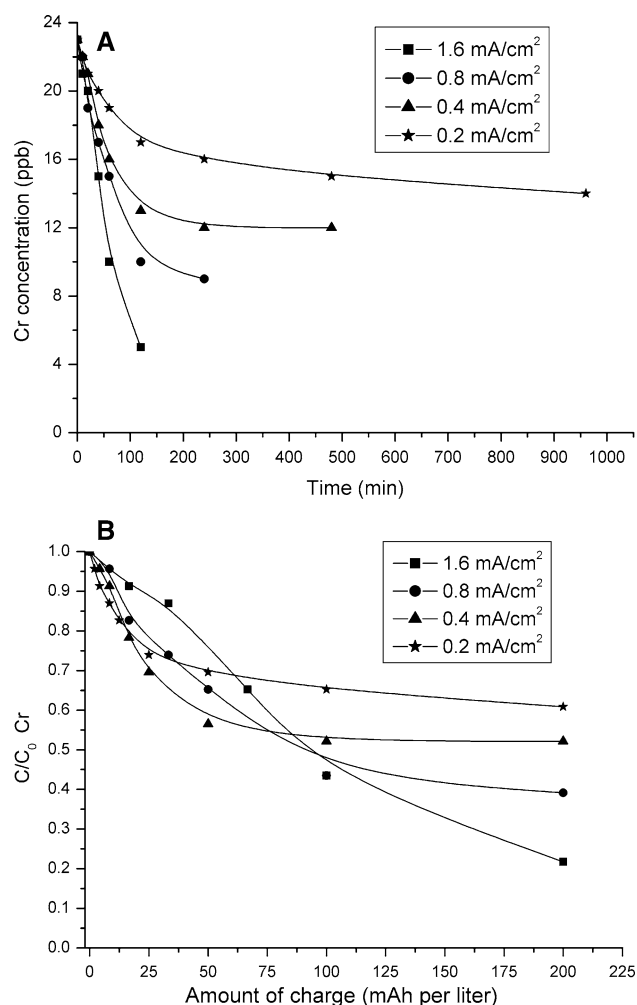


Fig. 3 Evolution of Cr concentration during electrocoagulation tests at different current densities: 0.2, 0.4, 0.8, and 1.6 mA cm⁻²; distance between the electrodes of 0.5 cm, stirred solution at 600 rpm. Concentration profile versus time (**A**), normalized concentration C/C_0 versus the amount of passed charge (**B**)

Cr (sample B), for different current densities in the range 0.2–1.6 mA cm⁻². The initial pH for the Ni sample was 7.6, while it was 7.4 for the Cr sample. These initial pH values are in agreement with optimal pHs for EC with Al electrodes reported in the literature [19].

As far as the pH trend is concerned, it shows a slight rise with increasing electrolysis time; this increase being more evident in the tests carried out at higher current densities. The final pH values for the Ni samples are 8.3, 8.2, 7.7, and 7.5, while for the Cr samples, they are 8.0, 7.8, 7.6, and 7.5, at 0.2, 0.4, 0.8, and 1.6 mA cm⁻², respectively. Vik et al. [11] reported that the removal of Ni and Cr from water by electrocoagulation causes pH increases at an initial pH of about 7, which they ascribed to hydrogen evolution and the generation of OH ions on the cathodes. Moreover, OH ions can partially combine with Ni²⁺, and with Cr³⁺ ions, to form insoluble hydroxide precipitates Ni(OH)₂ and

Cr(OH)₃, respectively. However, it is important to note that this depends on the solubility product for each species [18, 22, 24].

Figure 5 depicts the behavior of the conductivity for the different current densities. A decrease in this parameter with time has been observed in both the Ni- and Cr-containing samples, while in both cases, such a decrease is more pronounced at higher currents. This phenomenon is caused by the decrease in the concentration of all ions in the solution and the formation of hydroxide precipitates during the treatment.

The cell voltage in the experiments increased due to the fact that the conductivity decreased. As reported in the literature [9, 14], when the experiments were carried out at high current densities, high overpotentials were observed, due to the rise of both kinetic and concentration overpotential.

In addition, a simultaneous removal of selenium (Se), strontium (Sr), and barium (Ba) was observed during the experiments carried out with the Cr-containing sample. Table 3 shows the concentration values at the beginning and at the end of the processes. An increase in current density improved the removal rate of Se, Sr, and Ba, in addition to that of the main pollutants. WHO International Standards for Drinking-water recommend a maximum allowable concentration of 10 ppb for Se, based on health concerns. Even though the data for possible abatement of Se require careful confirmation, it can be noted (Table 3) that the residual Se concentration in the present tests is below this value. WHO does not refer to Sr and Ba. However, the results at the high current density show abatement greater than 50 % for Sr and about 100 % in the case of Ba.

3.4 Electrode degradation

It is known that in the course of the electrocoagulation process, the electrodes undergo drastic chemical changes. This is intrinsic in the working operation of the anode, being a sacrificial electrode, but it also occurs with the cathode, depending on the electrolyte composition and pH. As far as the anode is concerned, the Al surface is covered by a thin passivating oxide layer which prevents the uniform dissolution of the metal to homogeneously release Al³⁺ over the entire electrode surface. Thus, anodic dissolution of Al occurs through the breaking up of the passivating layer, leading to a highly localized corrosion (pitting) of the electrode surface. The degree and morphology of such a localized attack, depend on the presence and the concentration of halide ions (particularly Cl⁻ and F⁻), and on the applied voltage. Pitting, which is a highly localized and penetrating form of corrosion, leads to the creation of small holes or craters on the metal surface, sometimes visible to the naked eye [7]. Even though

Fig. 4 Variation in the pH during the electrocoagulation process at different current densities, 0.2, 0.4, 0.8, and 1.6 mA cm⁻² for the samples containing Ni and Cr; distance between the electrodes of 0.5, stirred solutions at 600 rpm

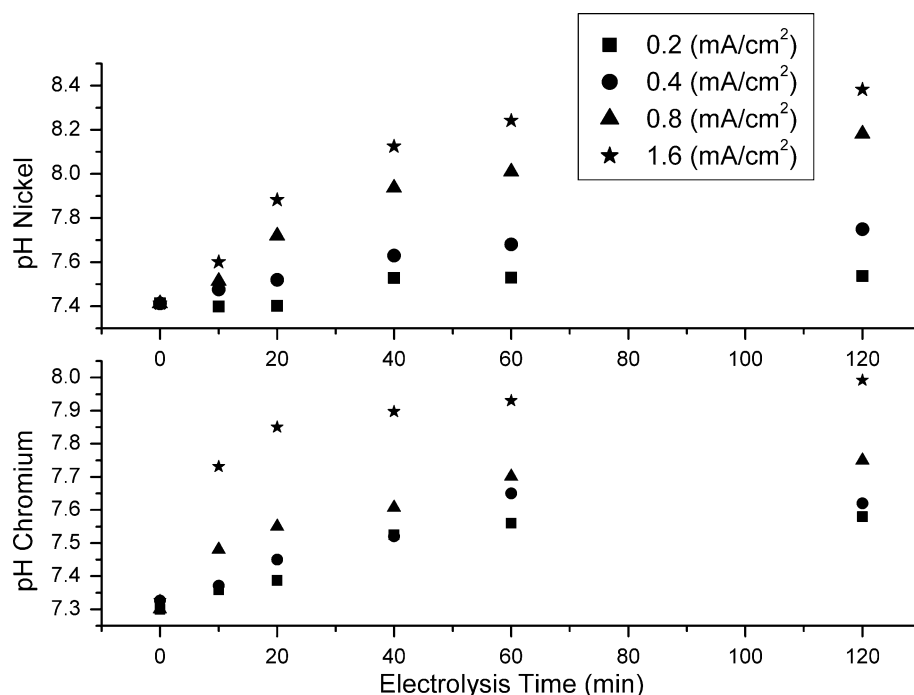
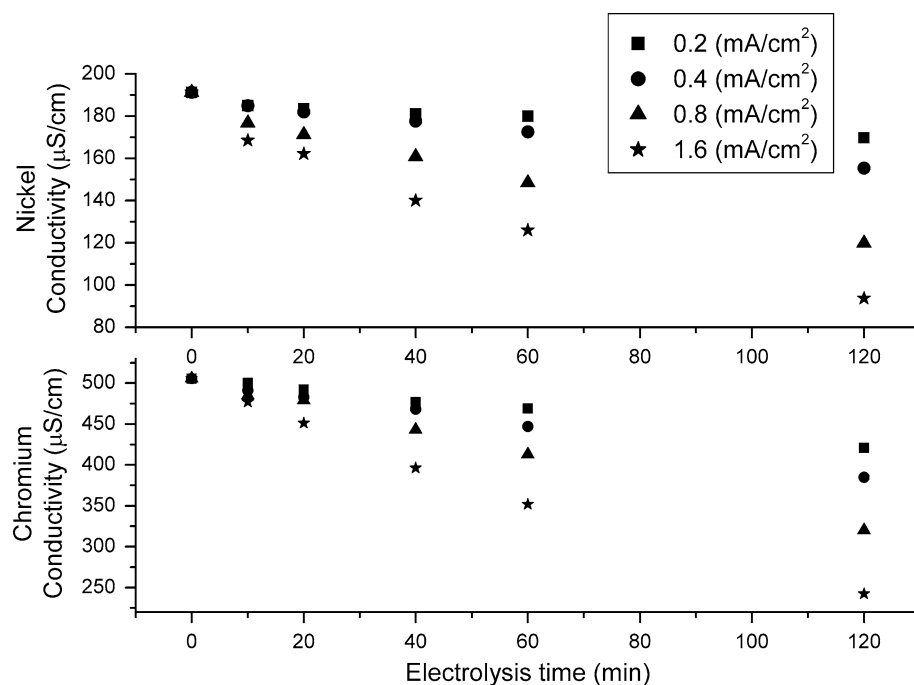


Fig. 5 Variation in the conductivity during the electrocoagulation process at different current densities, 0.2, 0.4, 0.8, and 1.6 mA cm⁻² the samples containing Ni and Cr; distance between the electrodes of 0.5 cm, stirred solutions at 600 rpm



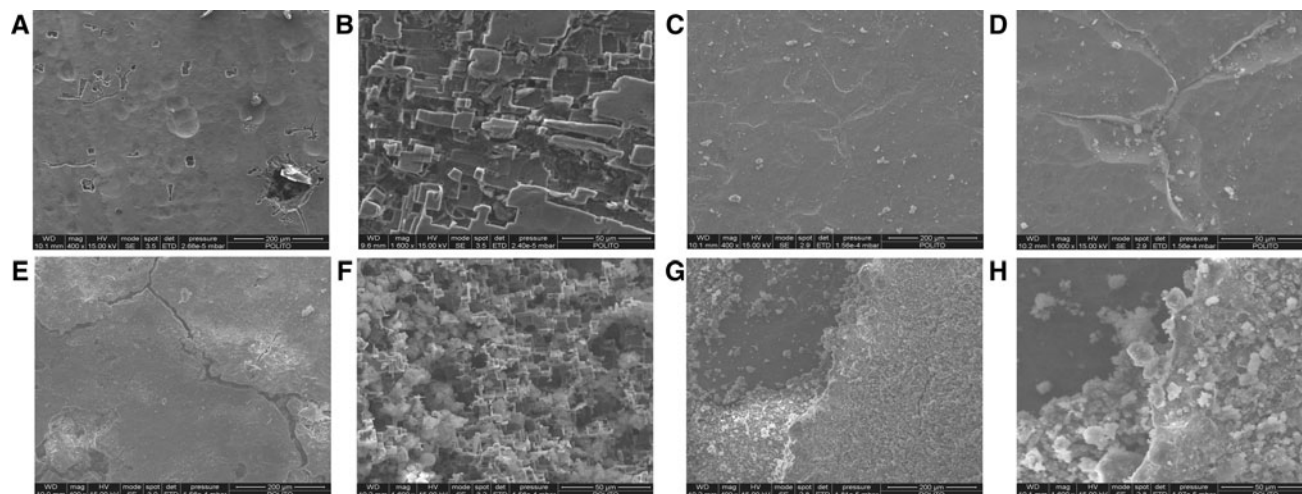
localized, the Al corrosion is responsible for the formation of Al³⁺, which influences the electrocoagulation efficiency, particularly in the presence of chloride ions in the solution [19]. A drawback of the localized dissolution of Al anodes, compared to a uniform dissolution of a metal surface, is caused by the increased degradation of the electrode due to the penetrating effects of pit formation, which leads to the electrode deterioration even for relatively small amounts of dissolved Al. In some cases, exfoliation corrosion can also

be observed on the Al anodes, as shown in Fig. 6A and B (Al anode used for the treatment of the Ni-containing sample) and Fig. 6E and F (Al anodes used for the treatment of Cr-containing sample). This phenomenon has been attributed to an attack of selective parallel layers on the metal surface, which continues along the grain boundaries and propagates through the crystal grains [25].

Also, the Al cathode can be subjected to important chemical changes during the electrocoagulation process.

Table 3 Co-removal values of the concentrations at the beginning and at the end of the electrolysis process in the Cr sample

	Time (min)	0.2 mA cm ⁻²	0.4 mA cm ⁻²	0.8 mA cm ⁻²	1.6 mA cm ⁻²
Selenium (ppb)	0	6	5	4	4
	120	4	4	3	2
Strontium (ppb)	0	224	226	253	250
	120	189	146	153	99
Barium (ppb)	0	12	12.2	15.9	15.6
	120	11.5	0	0	0

**Fig. 6** SEM micrographs showing the morphology of Al electrodes after 50 h of electrocoagulation treatment for both the samples containing Ni and Cr at two magnification levels, $\times 400$ (A, C, E, G) and $\times 1,600$ (B, D, F, H): A, B Al electrodes employed as anodes

and C and D as cathode for the treatment of the water sample containing Ni. E and F Al electrodes employed as anodes and G and H as cathode for the treatment of the water sample containing Cr

These changes cannot be ascribed a corrosion process, but are the consequence of the deposition of a film on the cathode surface (Fig. 6G, H). According to the EDS analysis, the deposited film is composed of calcium carbonate and magnesium hydroxide due to surface precipitation of the inorganic salts. The formation of these type of inorganic films strongly depends on the pH and composition of the water sample (Ca^{2+} , Mg^{2+}). The insulating layer formed on the electrode could increase the applied voltage sharply and result in a significant decrease in the process efficiency [19]. This can be a major operational problem concerning the process, and it affects the longevity of electrode [9]. On the other hand, this phenomenon could be advantageous when the goal is to reduce the Mg^{2+} and Ca^{2+} concentration in the solution, but in this case is necessary to remove the film from the cathode, to avoid the increase of the electrical resistance of the cell that could interfere in the of Al^{3+} generation process.

Nikolaev et al. [26] studied various methods to control electrode passivation, including: changing the polarity of the

electrode, hydro-mechanical cleaning, introducing inhibiting agents, and mechanical cleaning of the electrodes.

In the present case, the most efficient and reliable method of electrode maintenance could be periodic mechanical cleaning of the electrodes.

No film was deposited on the cathode used for the sample A (Fig. 6C, D).

4 Conclusions

This study has shown the high potentiality of using the electrocoagulation process, in the treatment of drinking water contaminated with Cr and Ni. The most efficient operative condition which was found for the investigated well water is parallel plate Al electrodes at a distance of 0.5 cm, under stirring and with a current density in the range $0.8\text{--}1.6\text{ mA cm}^{-2}$. The removal of Cr was slower than the removal of Ni.

In this study, a simple batch laboratory cell was used under conditions which are rather unlike real

electrocoagulation reactors. In future study, in view of the refinement of the operating conditions, a flow-through laboratory reactor will be designed and used.

Electrocoagulation also promoted the removal of Se, Sr, and Ba. After 50 h of electrolysis, the anodes showed a relevant pitting corrosion. Exfoliation corrosion was also observed at the anode. On the other hand, a film was deposited on the surface of the cathode electrode used for the Cr containing sample after 50 h of electrolysis, depending on water hardness; this phenomenon can be advantageous when the goal is to reduce the Mg^{2+} and Ca^{2+} concentration in the solution, but causes an increase in the electrical resistance of the cell. However, these problems could be handled by periodically removing the film by means of mechanical cleaning of the electrode.

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